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Geothermal energy potential of southwestern of Saudi Arabia "exploration and possible power generation": A case study at Al Khouba area – Jizan

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ABSTRACT

Saudi Arabia is enriched by many geothermal resources located mainly at the western and southwestern parts. These resources are related to the general tectonic activity of the Red Sea and associated with a series of volcanic rocks and ridges. The Jizan area is considered as a promising geothermal system that includes a number of structural-related hot springs with surface temperature from 46 °C to 78 °C. The present work aims mainly to explore and locate the potentiality of these resources through analyzing the available satellite images, applying a number of geo-indicators and performing a 2D electric geophysical survey, as well as estimating the geothermal reserve potential for possible energy production.

The available ETM, TM 5 and 7 Landsat satellite images are interpreted. A geo-thermometric study was performed to determine the subsurface formation temperature, heat flow and water type. A number of 2D electric profiles are conducted in the study area to investigate the subsurface orientation of the geothermal anomalies. The recorded resistivity data are processed and interpreted to delineate the lateral and vertical configuration of the possible geothermal reservoirs.

This study revealed the presence of many good geothermal anomalies in Jizan province of which Al Khouba geothermal resource is considered the most important. It is characterized by good surface petro-thermal properties (high temperature, up to 78 °C and good flow rate) and promised subsurface characteristics (good vertical and lateral extensions), as well as potential thermal properties.

The estimated thermal parameters are found to be 144 mW/M^2, 318 kJ/kg and 133 °C for heat flow, discharge enthalpy and subsurface temperature, respectively. A good geothermal potential of 17.847 MWt is estimated for Al Khouba hot spring providing a reservoir area of 1.125 km^3. We do recommend the official authorities to investment, encourage and support the future scientific research in this area.

Contents

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1. Introduction

Geothermal resources are considered among other renewable resources (wind, solar, biomass, tidal, etc.) that can be used efficiently for clean energy production [1,2].

These resources, either in the form of subsurface thermal collectives (hot dry rock) or surface hydrothermal hot springs, are considered among the most important sources of renewable energy. The majority of these geothermal resources are concentrated in the western and southwestern parts of the Kingdom, in

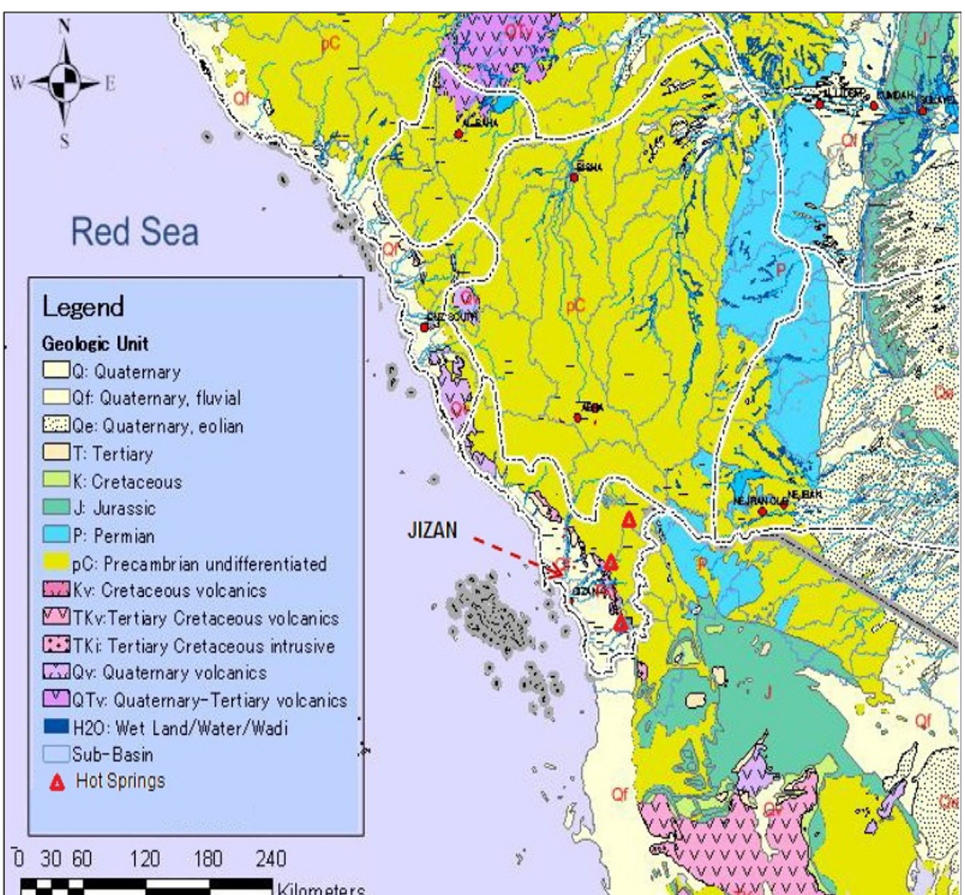

Fig. 1. Geologic map of the Jizan area showing the different encountered rock units.

the form of hot springs and surface volcanic eruptions or what is called "Harrats". The upcoming thermal waters reach the surface through a complex grid of structural elements which, in general, follow the main tectonic elements and activities prevailing in the whole Red Sea area. In so doing, a large number of promised geothermal anomalies and hot springs are allocated along the coastal parts of Gulf of Suez of Egypt, the eastern coasts of the East African Rift countries, and the western and southwestern parts of the Saudi Arabia. These springs owe their existence to tectonic (or volcanic) heating associated with the opening of the Red Sea/Gulf of Suez rift [3–11]. So, studying these geothermal targets as possible sources for renewable energy in Saudi Arabia is of prime interest [8].

However, the geothermal energy is not actually studied in Saudi Arabia. Only few studies had dealt with these resources in the last three decades. The most important work was that done by Al Dayel, 1988 [12], who studied the hydro-chemical properties of the geothermal springs and the geology of the volcanic Harrats encountered along the western coastal parts of the Red Sea. He classified the geothermal anomalies in terms of potentiality into zones with high heat flow (Harrat Khaybar and Harrat Rahat), zones with a locally significant heat flow (Harrat Kishb) and zones with heat flow spots above average (Harrat Hutaym and Harrat Lunayyir). He also concluded that the thermal waters of the hot springs (Al-Lith and Jizan) are relatively recent, having circulated rapidly in deep aquifers [12].

Another good work was done by Alnatheer, 2007, who discussed the future of applying the different aspects of renewable energy "including the geothermal resources" in Saudi Arabia. His work is mainly concentrated on giving a quantitative assessment of the costs, savings and the environmental benefits of utilizing the renewable energy as a part of an electric utility integrated resource planning project in the Kingdom [13]. A more recent work was done by Lashin and Al Arifi [8]. They studied the geothermal resources in the southwestern parts of Saudi Arabia, through enhancing an integrated remote sensing, Landsat image

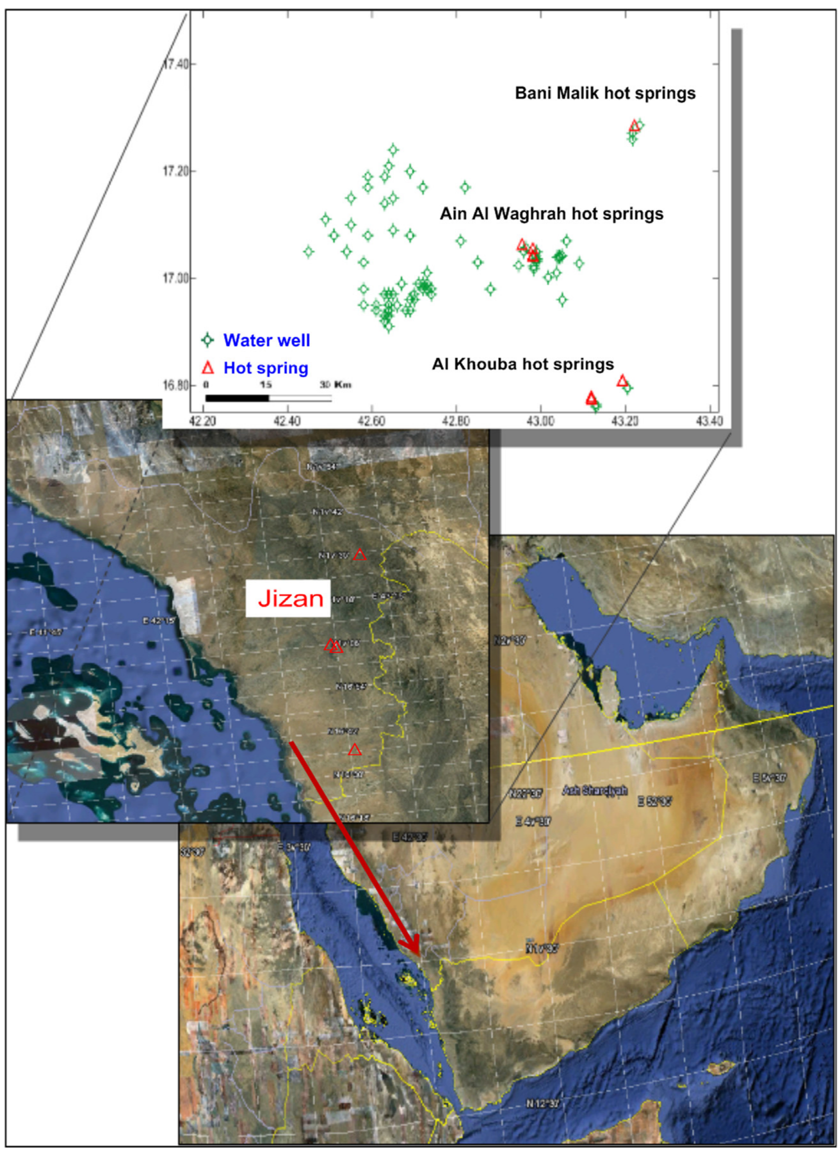

Fig. 2. Location map of the Jizan area illustrating the location of the main geothermal targets and surrounding water wells.

analysis and geo-thermometer study. They concluded that good and attainable geothermal sources with promised petro-thermal parameters are encountered at many locations in Jizan area.

Analysis of Landsat satellite images and image processing methods is very attractive, fast and reliable tool for various applications and management [14,15]. These methods provide a framework for implementing the stratification techniques which can be used for many purposes such as, watershed analysis, terrain and drainage basin analysis, as well as many geological and geophysical applications [16]. In the present work, these techniques are generally applied in the geothermal active locations in the Jizan area, to quantify the effect of land cover on the geomorphology and slope of watersheds, and more specifically to investigate the topographic nature of the area occupied by the hot springs [8].

On any preliminary study of geothermal systems, the geo-thermometers are proved to be very effective tools which could be used to shed light over the prevailing subsurface geothermal regimes. Different types of water geo-thermometers were developed from the mid-1960s to the mid-2010s. The most important ones are the Silica, Na/K and Na–K–Ca geo-thermometers. Some other geo-thermometers are based on the Na/Li, Li/Mg, K/Mg ratios and Na–K–Mg relationships. Many workers had dealt with applying the geo-thermometers in subsurface temperature studies [17–24]. The geo-thermometers are usually used to estimate some important geothermal parameters such as heat flow, discharge enthalpy and subsurface formation temperature.

This work presents part of the results concluded from a research project that aims mainly to re-evaluate the geothermal potential of the resources encountered in the western and south-western parts of the Kingdom of Saudi Arabia, beside discussing the possibility of its utilization in an economic industrial scale for renewable energy production and other thermal applications. It constitutes a preliminary study for exploring, locating and evaluating the geothermal potential of the hot springs scattered at many parts of the Jizan area. The significance of this work stems from the fact that it is the first time in Saudi Arabia to deal with the geothermal resources as a new possible source for renewable energy.

Generally, the main tasks of this study can be categorized as to (1) determining the location of the geothermal collectives and hot springs through analyzing the Landsat satellite images, (2) performing a geo-thermometric study based on the chemical analyses of the collected water samples, (3) conducting a 2D geophysical electric survey to investigate the subsurface pattern and give clear and obvious signatures about the prevailing structure system, and (4) enhancing a quantitative geothermal reserve estimation.

2. Geologic setting

Electricity generated from geothermal power plants is an entirely renewable and reliable form of energy, but its application depends completely on the geology of the site. The Jizan area is located in the southwestern part of Saudi Arabia between longitudes 42.0–43.8°E and latitudes 16.5°–17.50°N with an area of 40,475 km^2. It constitutes part of the Arabian shield which is a part of the Precambrian crustal plate and consists of igneous rocks, basalts, diorites, gabbros and mica-schist. During the Tertiary period, the shield was separated from the adjacent African shield by the Red Sea crust. Sedimentary coastal plain has been formed on the area between the escarpment of the shield and the Red Sea [8,25].

The geology of the Jizan area is divided mainly into two main features: the near shore deposits which include many valleys draining towards the sea and the crystalline basement (granite) and metamorphic rocks in the eastern portions of the Jizan which includes number of promised hot springs. In the absence of lithologic or structural units more favorable to the existence of reservoirs, all evidences indicate that these granite units act as a reservoir, and that the water rises to the surface either through fractures or lithologic/structural discontinuities; i.e. fracture separating the granite unit from its metamorphic or crystalline host rock [12]. The geological map of the Jizan area (Fig. 1) exhibits rock units ranging in age from Precambrian to Quaternary. The Precambrian basement complex consists mainly of three rock units, i.e.; Sabya formation, the Baish group and Halaban group. The other rock units encountered in the Jizan area are represented mainly by a variety of meta-sedimentary units, some intrusive rocks, Quaternary rocks mainly olivinitic basalt and thick coastal plain of Quaternary sediments. The following is a brief description of main features of these rock units.

2.1. Precambrian basement complex

2.1.1. Sabya formation

The Sabya formation consists of meta-sedimentary rocks of highly complicated group of schists (quartzite, quartz pebble-conglomerate, argillite, limestone, dolomite and early basalt flows intruded by sills of hypabyssal gabbros), which outcrops mainly in the mountainous regions and covers about 40% of the exposed bedrock area in the Jizan area.

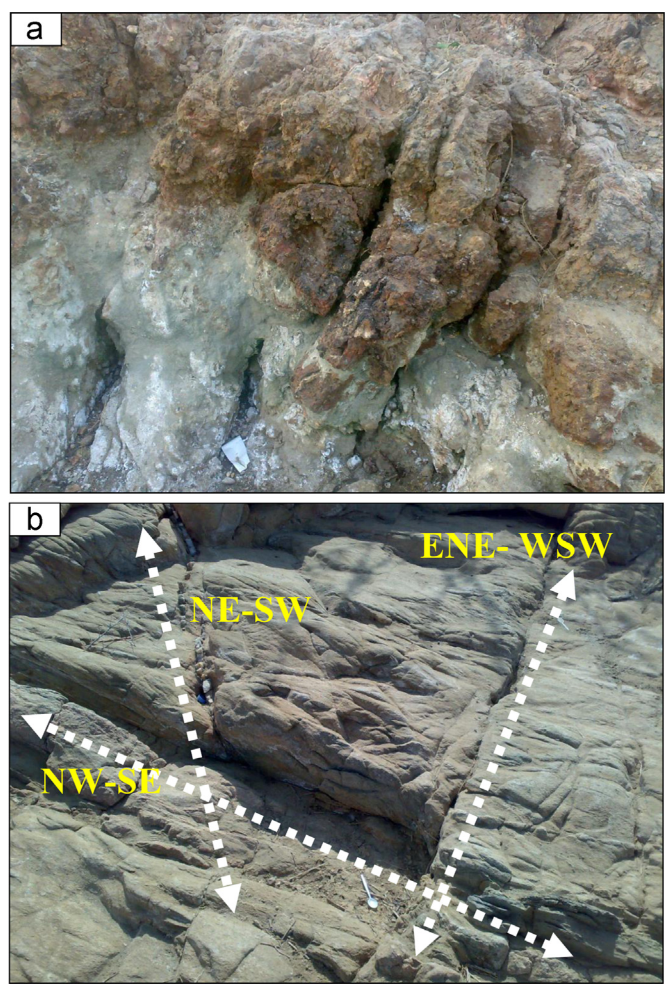

Fig. 3. (a) Altered granitic rocks due to thermal effect. (b) The structural and fracture system that control the whole geothermal resource at Al Khouba area.

2.1.2. Baish group

The type locality of this group is located in the Wadi Baish and consists of exposed greenstones of metabasalt and diabase. The Baish greenstones cover a narrow zone in the northeastern part of the Jizan area and surrounding the upper embankments of Wadi Sabya and Wadi Qasi. They were described as locally pillow-structured and spilitic where interbedded with the upper part of the Sabya formation.

2.1.3. Halaban group

Two main different rock units constitute the Halaban group: one of sedimentary origin, "the meta-sedimentary unit" which consists of graywacke and siltstone probably derived from the older igneous rocks, while the other of volcanic origin, "the meta-volcanic unit" which comprises andesite, basalt flows, pillow lava, dacite and pyroclastic rocks.

2.2. Meta-sedimentary units

The meta-sedimentary rock units encountered in the Jizan area is represented mainly by graywacke and siltstone probably derived from the older igneous rocks, pyritiferous slate at Damad area as well as Carbonaceous slate, minor metaconglomerate, biotite schist and imperfect beds of marble completely intruded by gabbros.

2.3. Intrusive rocks

These include rocks ranging in age between Precambrian and early Cambrian like foliated granite, syenite, monzogranite, gabbro and diabase, and Wajid sandstone.

2.4. Quaternary rocks and sediments

The Quaternary rocks are represented by various vent cones of alkali olivinitic basalt. Such olivinitic basalt is usually found between Wadi Jizan and Wadi Baish and is dated in age from 5 Ma to recent. Two main basalt cones are found in Jizan area, one at the north (Jabal Akwat Ash Sham) and the other at the south (Akwat Al Yaman). Most of the Quaternary sediments are found along the coastal plain of the Jizan area. These sediments are of prime interest, as they encounter the main water aquifers in the Jizan area and are represented mainly by eolian sands and alluvial deposits.

Fig. 2 shows that the main recognized geothermal resources are originating from hard crystalline rocks and are closely located in the eastern part (away from the coastal plain) in areas vary topographically from low-land with medium slopes (Al Ardah and Al Khouba) to more complicated and high slope (Bani Malik). Fig. 3, on the other hand, illustrates the highly fractured granitic rocks and the whole structural pattern (NW-SE, NE-SW and ENE-WSW) that controls the geothermal system at Al Khouba area, as well as the altered granitic rocks.

2.5. Field surveys and recent geothermal activities

The data collected in this work came from a number of field trips and site visits that are arranged for more than 2 years ago, to the proposed hot springs. These field surveys aimed mainly to determine precisely the locations of the hot springs, exploring the possibility of finding new possible hot anomalies, collecting water samples from the hot springs and other surrounding water wells and finally conducting a detailed geophysical 2D electric survey to investigate the subsurface orientation of the studied area. Table 1 shows the co-ordinates, the surface temperature, topographic

Table 1
Summarizes the co-ordinates and some field measurements of the different hot springs encountered at the Jizan area.

Location	Hot spring	Co-ordinates	Surface temp. (°C)	Elev. (M)	pH	TDS (ppm)	EC (μS cm^{-1})
Al Ardah	Ain Al Waghrah-1	17°02.124′ 42°59.374′	44	179.5	7.7	3592	5987
	Ain Al Waghrah-2	17°02.130′ 42°59.370′	45	180.7	7.5	8815	14,692
	Ain Al Waghrah-3	17°02.156′ 42°59.360′	57	178.0	7.2	3072	5120
	Ain Al Waghrah-4	17°02.160′ 42°59.365′	57	178.0	7.2	3076	5127
	Ain Al Waghrah-5	17°02.165′ 42°59.370′	45	178.0	7.2	3135	5225
	Ain Al Waghrah-6	17°02.960′ 42°59.390′	61	178.8	7.0	3066	5110
	Ain Al Waghrah-7	17°03.443′ 42°57.830′	57	167.5	7.6	2088	3480
Al Khouba	Ain Khulab	16°45.854′ 43°07.769′	78	160.0	7.4	2510	4183
Bani Malik	Bani Malik	17°16′11.2″ 43°13′08.6″	45	647.5	7.3	1290	2150

Fig. 4. Recent geothermal activity by the Jizan manipulation authority. (a) Infrastructures and refreshment places close to Al Khouba hot spring. (b) Road construction above the granitic plateau to facilitate going to the hot spring.

Fig. 5. Geothermal activity by the Saudi Ministry of Tourism. (a) Special places for Spa and medical purposes. (b) Geothermal-based swimming pools.

elevation and some measured field parameters for the different hot springs at the Jizan area [8].

A recent governmental geothermal activity at Al Khouba hot spring was enhanced by Saudi Ministry of Tourism and the manipulation authority of Al Khouba area. Two small scale projects (6 months/ SR 2,000,000) are now in progress for developing the geothermal area and utilizing its resources for direct purposes and low-grade temperature applications. The first is supported by the manipulation authority to develop the plateau area that is very close to the Al Khouba hot spring and providing it with the refreshment places and other infrastructure complements (Fig. 4). While the second is enhanced by the Saudi Ministry of Tourism to put Al Khouba geothermal system in the touristic map of Saudi Arabia as an attractive medical and refreshment area (Fig. 5). It aims to drill one shallow well that will hit the main fracture system of the hot spring, up to 75 m, to pump water and rise it through specific pipes to the close highly mountain area (south of the hot spring). A number of swimming pools, medical therapy, Spa and refreshment places are now under constructions.

3. Materials and methods

Different categories of methodologies are applied in this study. They include (1) an integrated analysis of the field survey measurements, Landsat, satellite image and the geo-thermometry data to determine the topographic nature and the thermal characteristics of the geothermal targets in the study area; (2) a detailed geophysical field survey using 2D electric resistivity; and (3) a quantitative geothermal reserve analysis and technical feasibility study of the main geothermal resource in the Jizan area (Al Khouba).

3.1. Landsat and satellite images

Due to the lack of detailed field surveying data regarding the geothermal targets to be investigated and the complicated topographic nature of their areas, it was very important to perform analysis for the Landsat and satellite images data. In this regard, a number of ETM, TM Landsat 5 and 7 images are analyzed. The most important topographic and terrain parameters (slope, aspect and terrain shade) which are used in the ground surface simulation are derived from DEM. The prevailing drainage basins, their patterns and lateral extensions are also determined. They may be displayed in either raster format or vector format. Raster images are the simplest, since there is a one-to-one correspondence between the catchment area grid and the final raster image. Pixels are color coded differently to indicate the size of the drainage by using various thresholds of catchment area as criteria for assigning the colors. Vector output is more involved since it requires that individual grid elements be linked into line segments or grouped into sequences of line segments (polylines). Each drainage is traced upstream from its terminal node until the catchment value is less than the drainage threshold.

In general, the main objectives of such analysis can be summarized as to (1) locate the different geothermal collectives and hot springs, in addition to their surrounding water wells; (2) identify the topographic elevations, the prevailing Wadis, main pathways, and entrances for the hot springs; (3) determine the drainage pattern; and (4) enhance a digital elevation model for the study area.

3.2. Geo-thermometric analysis

The geo-thermometric analysis is based on the chemical analyses of many water samples collected from hot springs and some neighboring close wells. These wells are selected to demonstrate the differences of the water type characteristics, if found, with that of the hot springs. Fifty water samples are collected and analyzed for the major cations and anions, as well as for minor elements. The hydrogen number of each sample, its total dissolved salts and electric conductivity are also measured. Temperature sensor is used for measuring the in situ temperature of the hot springs. A number of ternary (Cl–SO_4–HCO_3) and Giggenbach (Na–K–Mg) diagrams are constructed for the different encountered hot springs to classify the thermal water on the basis of major anions and cations and to indicate the prevailing subsurface thermal conditions.

3.2.1. Geo-thermometers

A variety of geo-thermometers, with good efficiency with low geothermal systems, are selected to measure the needed geothermal parameters. Theoretically, geo-thermometers can be used as indicators for both high temperature ($T > 150$ °C) and low temperature geothermal systems ($T < 150$ °C). Almost all the hot springs to be studied have a surface temperature less than 150 °C and ranging from 40 °C to 80 °C. ICEBOX-Watch 2.1 software is used for conducting the necessary calculations. The most important parameters to be concluded from this analysis are the chemical characteristics of the deep fluid, its actual subsurface temperature, discharge enthalpy and heat flow.

The scientific procedures followed in these analyses are mainly based on the work [17,18,21–24]. The silica geo-thermometers for Quartz and Chalcedony and the cation geo-thermometers of Na, K,

Ca and combinations of them are used in this study. Due to the low temperature nature of the investigated geothermal targets ($T < 150$ °C), the applied geo-thermometers are selected to cover a temperature range of 25–250 °C.

3.3. *Geophysical exploration (2D electric resistivity)*

Due to its high surface temperature and good subsurface petro-thermal parameters, Al Khouba hot spring is further investigated using the geophysical electric survey and evaluated for its possible geothermal potential. A number of 2D resistivity profiles are constructed using Schlumberger and Schlumberger–Wenner arrays at the area of Al Khouba hot spring (Fig. 6). These profiles are surveyed taken into consideration to cut through the main prevailing structural elements in the study area (NW–SE and NNE–SSW) and to detect the feed zones. Finally, these profiles are interpreted in order to delineate the configuration, the geometry and the subsurface orientation of the possible structures and fractures system as well as detecting the possible pathway for the arising hot water of the geothermal reservoirs.

The Syscal-Pro equipment with 72 multi- electrodes system is used for conducting the field survey using 5 (or) 10 m electrode spacing arranged along a profile. The electrodes location and elevation are measured using GPS and the designed electric survey is taken into consideration to keep the hot spring in the center of the grid.

3.3.1. *Processing of data*

Processing and analysis of data, as well as interpretation of electric resistivity data, is enhanced using RES2DINV software. The software operates large data sets collected with a large number of electrodes and can account the topographical effect along the

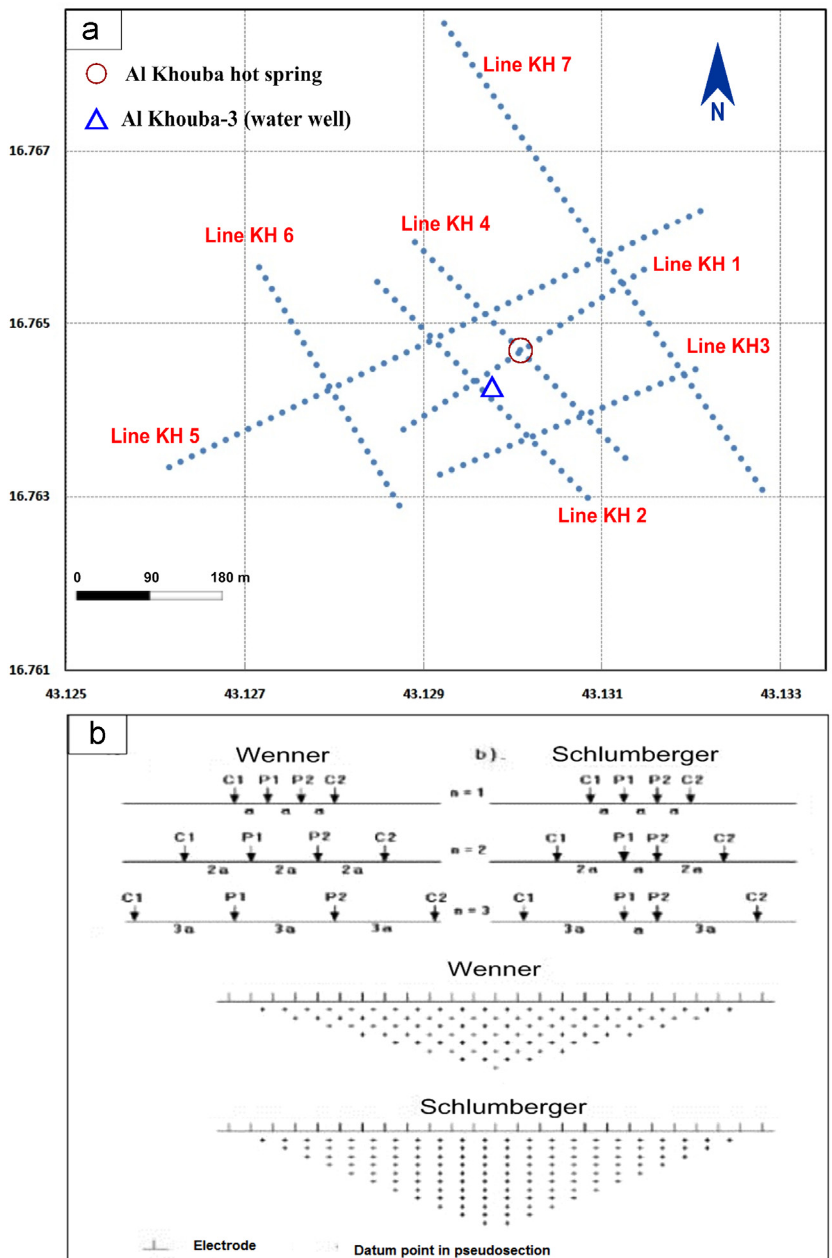

Fig. 6. (a) Base map of Al Khouba geothermal resource, showing the location of the 2D electric profiles. (b) Wenner–Schlumberger arrangement of electrodes.

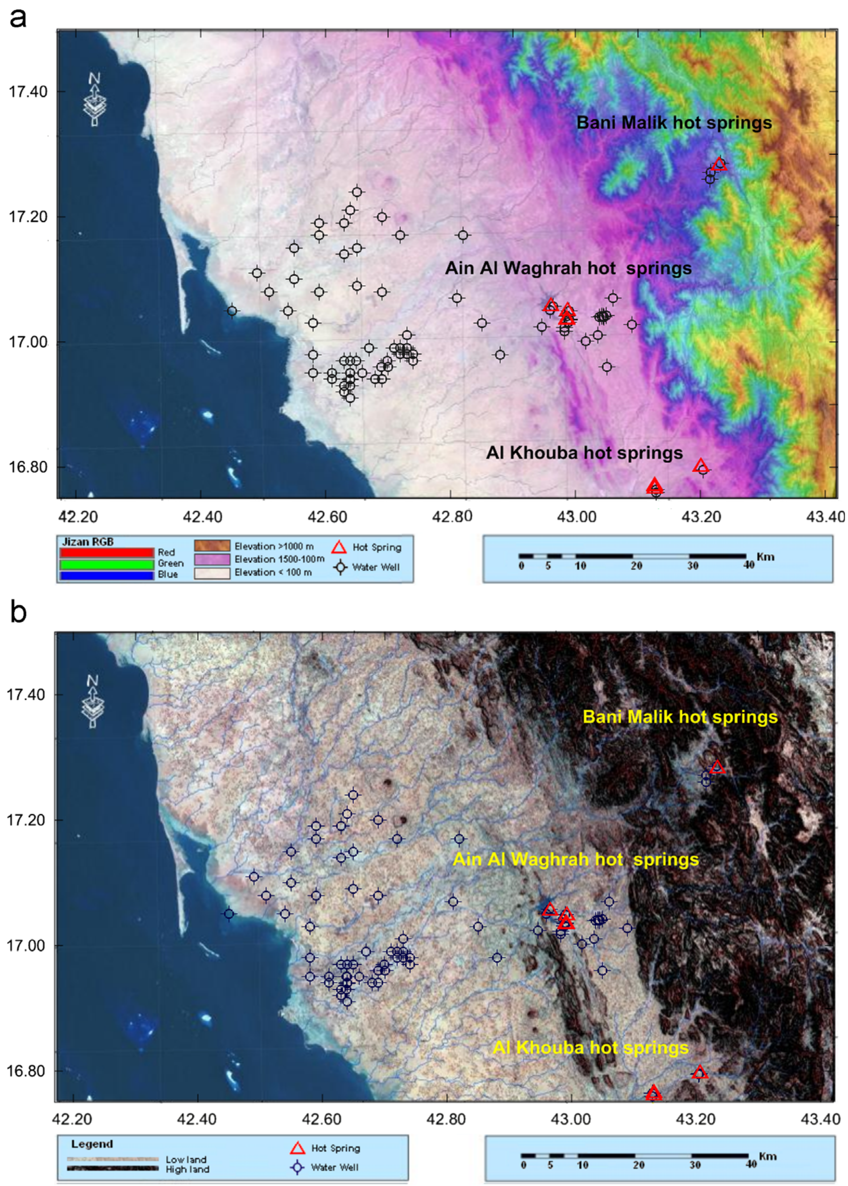

Fig. 7. (a) Digital elevation model map (DEM) of the Jizan area illustrating highlands in the eastern and northeastern portions, and (b) topographic map of the Jizan area indicating complicated ridges in the eastern part as compared with the simple coastal plains in the west (modified after [8]).

survey lines. The program runs a large number of iterations for calculating the true resistivity and gives the comparable root-mean-square (RMS) error of each trial. This error quantifies the difference between the measured resistivity values and the calculated from true resistivity model.

3.4. Geothermal resource assessment

Within a geothermal environment, multiple processes and rock properties over a great range of depths and distances define the system. Convection of water and conduction of heat from the hot rocks to the water are important elements which allow for the utilization of the resource. Target zones in geothermal systems where fluids can be extracted for electricity production span depths of 1000–3500 m have temperatures in the range of 250–350 °C, and permeability is sufficient to allow for enough fluids to be extracted. Gaining information about the geothermal system over as a large an area as possible in a wide depth range is beneficial for defining and managing the geothermal resource.

3.4.1. Reserve estimation

There are a variety of methods for estimating the production capacity of a geothermal resource. Statistical methods such as “volumetric-heat-in-place” assessments are sometimes done at this stage when surface methods indicate that resource parameters suitable for a geothermal development are likely but no direct reservoir measurements are available from wells [26]. The geothermal reserves of a certain geothermal reservoir can be estimated using the volumetric method. It involves the computation of the total heat energy stored in a volume of rock as compared to certain reference temperature. This will be the sum of the thermal energy stored in the rock matrix and the thermal energy of the fluid (water and/or steam) in the rock pore spaces. The basic assumption used in such calculations is that the stored heat energy in a certain reservoir is the sum of the energy of the fluid stored in the pore spaces and the energy of the hosting rock. Beside the temperature and its related parameters, other important reservoir parameters (volume, porosity and density of both rock and water) must be determined first before assessing the thermal potential of the reservoir [27]. The reservoir parameters

necessary for geothermal-reserve estimation (ϕ, ρ, T_i, thickness and volume, etc.) will be gathered from the interpretation of the geophysical data and from other geochemical analyses. The RESPAR software (ICEBOX, reservoir parameter module) will help in deriving of these parameters.

The total energy of the geothermal reservoir can be regarded as the sum of stored rock energy (E_r) and the energy stored by fluids in the pore spaces (E_f). It can be estimated using the following equation:

$$E_t = E_r + E_f = V(1-\phi)\rho_r C_r (T_i - T_o) + V\phi\rho_w C_w (T_i - T_o) \quad (1)$$

where E_t is the total thermal energy (J) in the rock (E_r) and fluid (E_f); ϕ is the reservoir porosity (%); V is the reservoir volume (m^3); $\rho_{r,w}$ are the densities of rock and water (kg/m^3); $C_{r,w}$ are the heat capacities of rock and water (J/kg °C) and T_i, T_o are the initial reservoir and the reference temperatures (°C).

Geothermal power potential (MW) can be estimated using the following relation:

$$\text{Power potential (MW)} = (E_t * RF * CE)/(PL * LF) \quad (2)$$

where E_t is the total stored energy (rock and fluid), *RF* is the recovery factor, *CE* is the conversion efficiency, *PL* is the geothermal plant life in years and *LF* is the load factor.

4. Results

The results implied from analysis of field survey measurements, Landsat and satellite images data are represented in Figs. 7–13. The first four figures (Figs. 7–10) represent the prevailing topographic, elevation model, drainage pattern and basin characteristics of the areas occupied by the hot springs. Figs. 11–13 show the distribution maps of the measured petro-thermal properties of the investigated hot springs.

The first geothermal system is located at Al Ardah area (east of Abu Arish city) more closely to the Dam Lake. Two hot spots including seven hot springs are found in this area with a surface temperature range between 43 °C and 61 °C. These hot springs

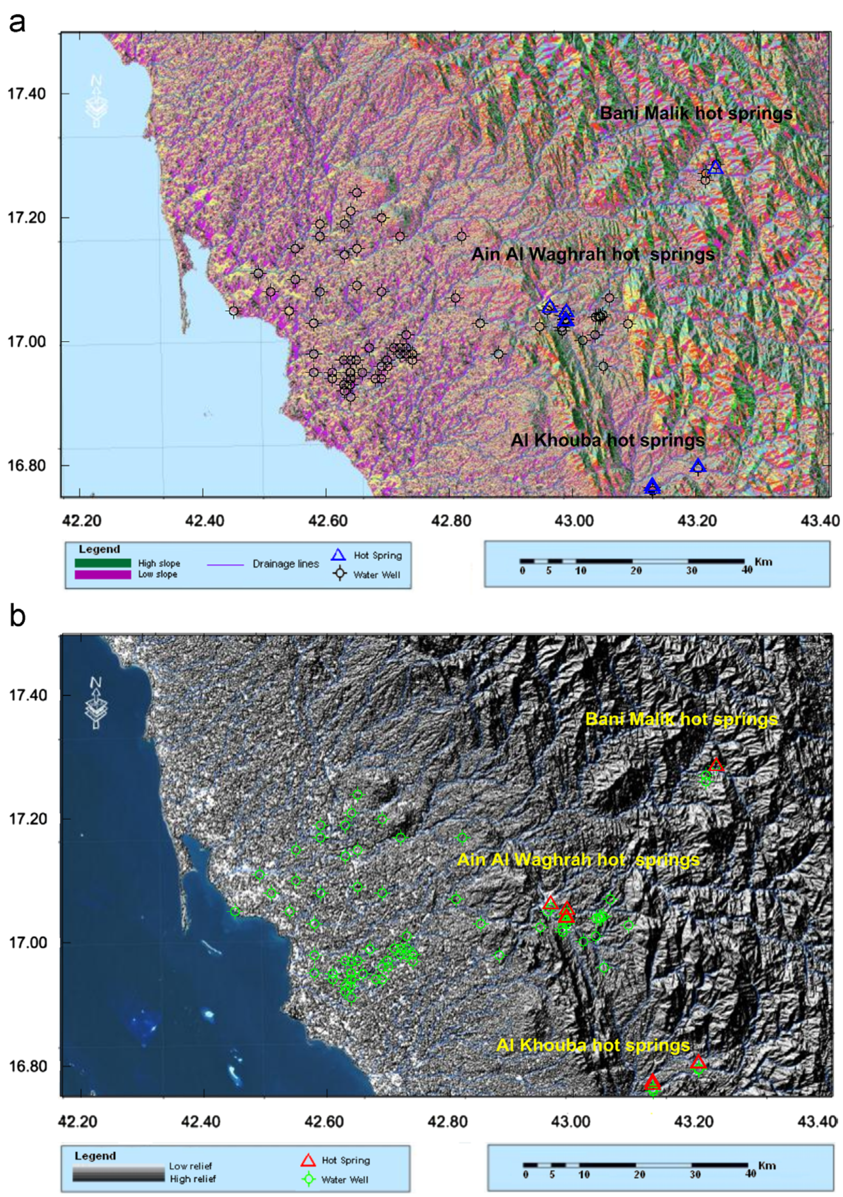

Fig. 8. (a) Slope map of the Jizan area showing an east–west decrease of slope towards the coastal parts, and (b) Sun-shaded relief map of the Jizan area showing the increasing order of shading towards the east and northeastern parts.

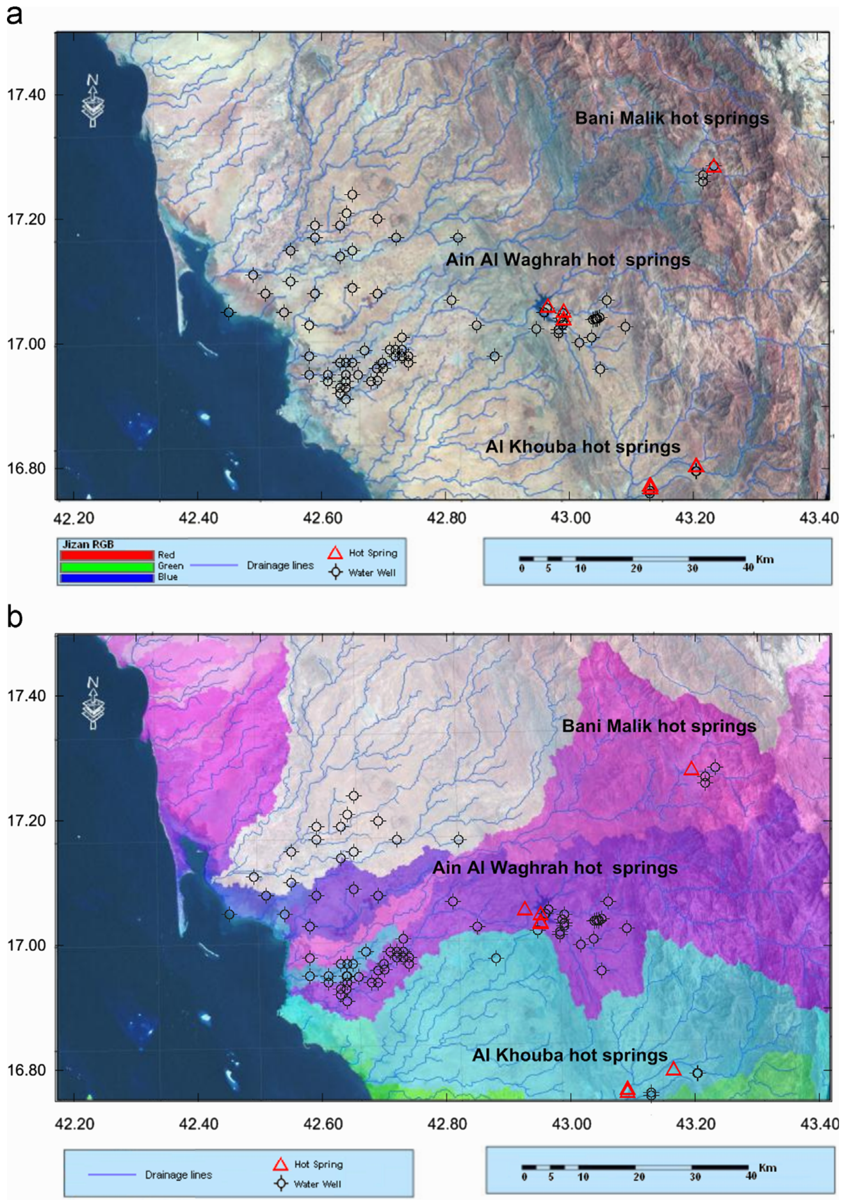

Fig. 9. (a) Drainage pattern map of the Jizan area illustrating the upstream (northeast) –downstream (southwest) prevailing dendertic pattern of the valleys, and (b) drainage pattern and basin map of the Jizan area illustrating the presence of different basins (modified after [8]).

are named Ain Al Waghrah-1 to 7. Six of these hot springs are originating from the same hot spot in front of the Dam Lake, while the seventh is located beside the Dam Lake and seems to be of a separate source. The second geothermal area is located at the southeastern of the Jizan, in an area called Al Khouba, which is a small city near the border of Yemen (20 km). One main hot spring of high surface temperature (78 °C) and fair to good flow rate is found. The third geothermal target is located to the northeast of the Jizan province in a very high and more complicated-topographic area (Bani Malik village). Bani Malik hot spring is originated from low-temperature (45 °C) system of highly fractured basement and metamorphic rocks. Few years ago, this hot spring is exploited by the Saudi ministry of tourism and utilized for medical therapy and refreshment purposes.

The petro-thermal parameters which are indicated from the geo-thermometric study are listed in Table 2. It shows the subsurface formation temperature (estimated using the Quartz, Chalcedony, Na, K, Ca geo-thermometers and combinations of them, i.e. Na–Ca and Na–K–Ca), weighted temperatures values, discharge enthalpy and heat flow. It appears clearly that the studied hot springs are attaining good and high geothermal parameters. Table 3, on the other hand, exhibits an example of the output analyses carried out by WATCH 2.1 software for one selected hot spring (Ain Al Waghrah-2).

The subsurface pattern of Al Khouba hot spring is investigated by interpreting the 2D electric resistivity profiles (Figs. 16 and 17). Majority of the detected geothermal feed zones are oriented along directions following the main structural elements in the Red Sea area (NW–SE, ENE–WSW). The geothermal reserve estimation assigns a good figure of 1.123×10^{17} J and power potential of 17.847 MWt, which is appropriate for limited power production (MWe).

5. Discussions

The following is an integrated discussion of the main concluded results from Landsat, satellite image analysis, field measurements,

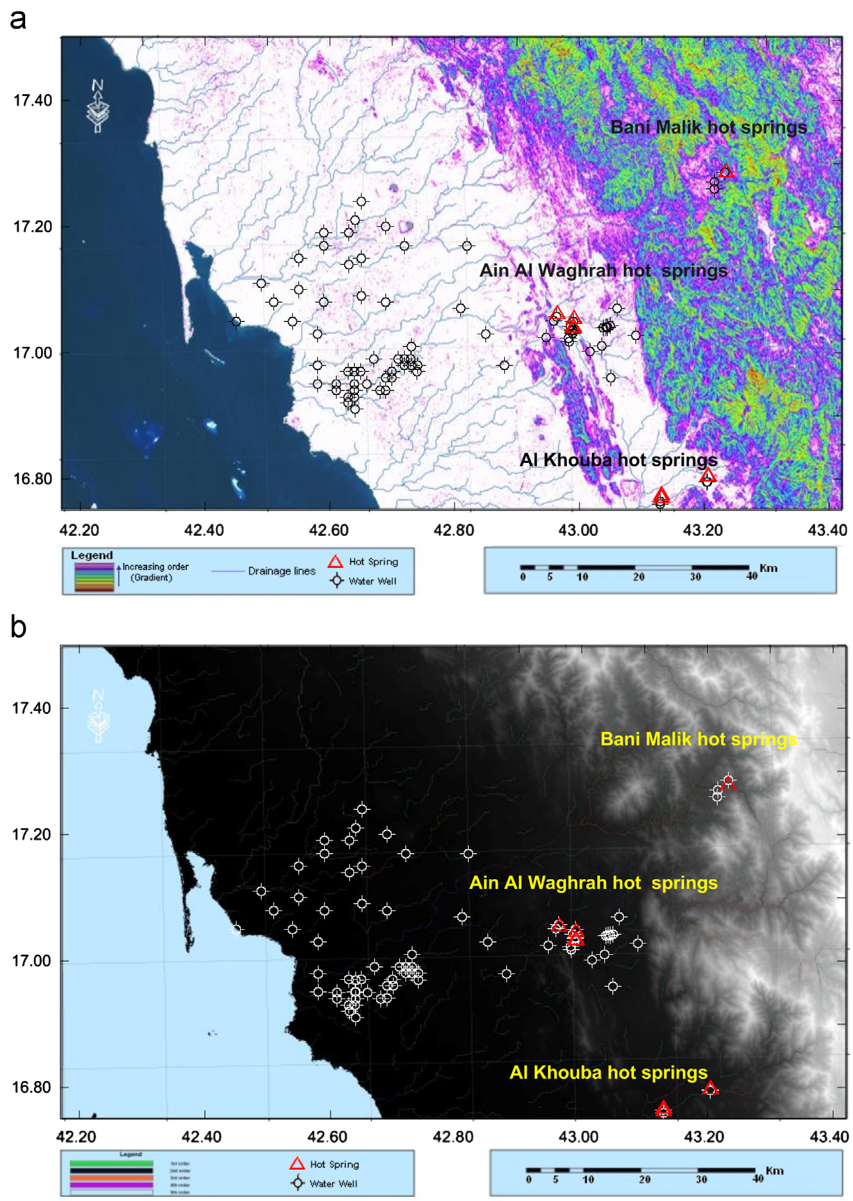

Fig. 10. (a) Stream line map of the Jizan area (modified after [8]) and (b) stream order (of DEM) map of the Jizan area.

geo-thermometry and geophysical interpretations as well as the geothermal power potential assessment.

5.1. *Landsat and satellite images*

Figs. 7–10 show the constructed Landsat and satellite image maps for the Jizan area. The digital elevation model and the topographic maps of the Jizan area (Fig. 7a and b) exhibit steep, complicated and high-land nature of the rock units encountered in the eastern and northeastern portions. Meanwhile, near the shore line, the coastal low-land areas are characterized by a gentle slope and simple structure. The slope map (Fig. 8a) shows an east–west decrease of slope towards the coastal parts [8].

The sun-shaded relief map (Fig. 8b) identifies the steepest down slope direction from each cell to its neighbors. It can be thought of as slope direction or the compass direction a hill faces, while the hill shade tool obtains the hypothetical illumination of ground surface by determining illumination values for each cell in a raster. It indicates an increasing order of shading towards the east and northeastern part of the Jizan area. The drainage pattern, drainage basin, stream line and stream order maps (Figs. 9 and 10) illustrate the northeast–southwest sea-ward running behavior (upstream–downstream) of the drainages which are mainly dendertic in pattern and constituting six different basins [8].

In general, the hot springs encountered at Al Ardah (Ain Al Waghrah) and Al Khouba areas are occupied in a medium to low land with little slopes, while Bani Malik hot springs are located in a very tough, high (> 650 m above sea level) and steep slope topographic area (complex ridge of Precambrian rocks).

5.2. *Geo-thermometric*

Some important petro-thermal parameters (subsurface formation temperature, discharge enthalpy and heat flow) are interpreted, based on the results of the geo-thermometer data. Figs. 12b and 13a and b exhibit the lateral distribution maps of these parameters. The subsurface temperature map shows regular normal distribution of the subsurface temperature for the hot springs and water wells surrounding them. The temperature range for these wells is 38–80 °C (Fig. 12b). On the other hand, a much

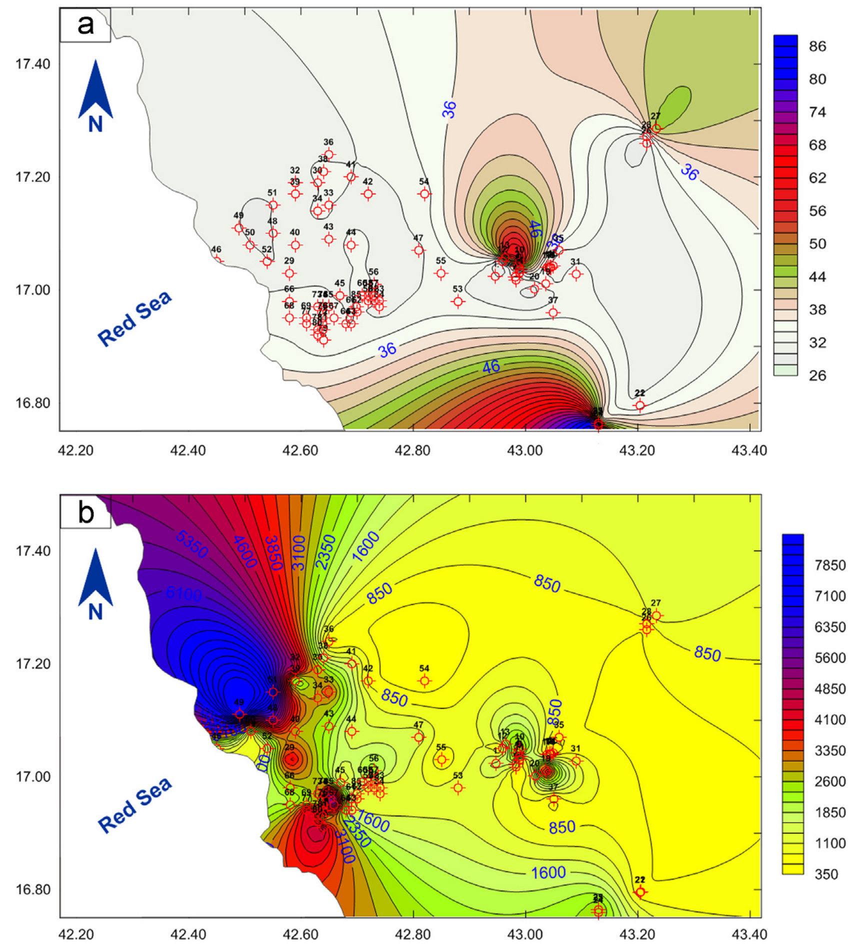

Fig. 11. (a) The surface temperature map of the Jizan area and (b) the total dissolved salts map of the Jizan area.

higher range of subsurface temperature (95–152 °C) is indicated for the hot springs. This is clearly indicated by the dense blue-to-red colored contour lines, especially in the areas occupied by Ain Al Waghrah, Al Khouba and Bani Malik hot springs. The maximum value of subsurface temperature (151.4 °C) is exhibited by Ain Al Waghrah-2 hot spring.

The discharge enthalpy map (Fig. 13a) assigns high enthalpy values for the hot springs (180–255 kJ/kg) and low enthalpy values for the surrounding water wells, with a general trend of decreasing towards the shore line (100–160 kJ/kg). The heat flow distribution map ensures the same concluded results from the discharge enthalpy and subsurface temperature data. Good and high heat flow values are recognized in the areas of Ain Al Waghrah, Al Khouba and Bani Malik hot springs (Fig. 13b). T he recorded heat flow values in these areas reach as high as 210 mW/M^2 [8].

5.2.1. Classification of thermal fluids and water type

Fig. 14 shows the Cl–SO_4–HCO_3 diagram of Al Khouba hot spring, where water samples collected from the hot spring and some close water wells are plotted. Regarding the diagram, the different types of thermal waters can be distinguished (mature waters, Cl, SO_4 dominated waters and peripheral waters, HCO_3).

Most of data points are located in the mature water area along the Cl–SO_4 line and more closely to the chlorine point. Two data points belonging to two water wells in Al Khouba area are clustered at the volcanic water area with an increasing content of the sulfate content, while those of the hot spring are located at the mature water area.

5.2.2. Giggenbach diagrams

Giggenbach diagrams are powerful graphical techniques that are used widely to evaluate the water–rock interaction conditions by use of Na, K, Mg and Ca contents of discharge waters and a derivation of the geothermal solute equilibrium using Na–K–Mg–Ca geo-indicators [28,29]. In this study the Na, K, Mg diagram is used to indicate the subsurface geothermal condition at which the dissolved ions of the surface upcoming thermal fluids are originated. Fig. 15 represents the constructed Na, K, Mg Giggenbach diagram for Al Khouba hot spring. The data points of the thermal fluids are located behind the 75° Mg–K temperature line and between the 200° and 220° Na–K temperature lines. Only one exception is represent by Al Khouba-3 well which is located between the 75° and 100° Mg–K temperature lines.

5.3. Geophysical interpretation

The interpretation of electric resistivity data resulted in a number of pseudo-electric, true resistivity and geo-electric cross-sections (Fig. 6a). These sections are mainly concerned with detecting the source of the arising geothermal water, detecting feed zones, the effecting structural elements and the possible facture system. Figs. 16 and 17 show two interpreted geo-electric profiles crossing Al Khouba geothermal hot spring (lines KH 1 and KH 4).

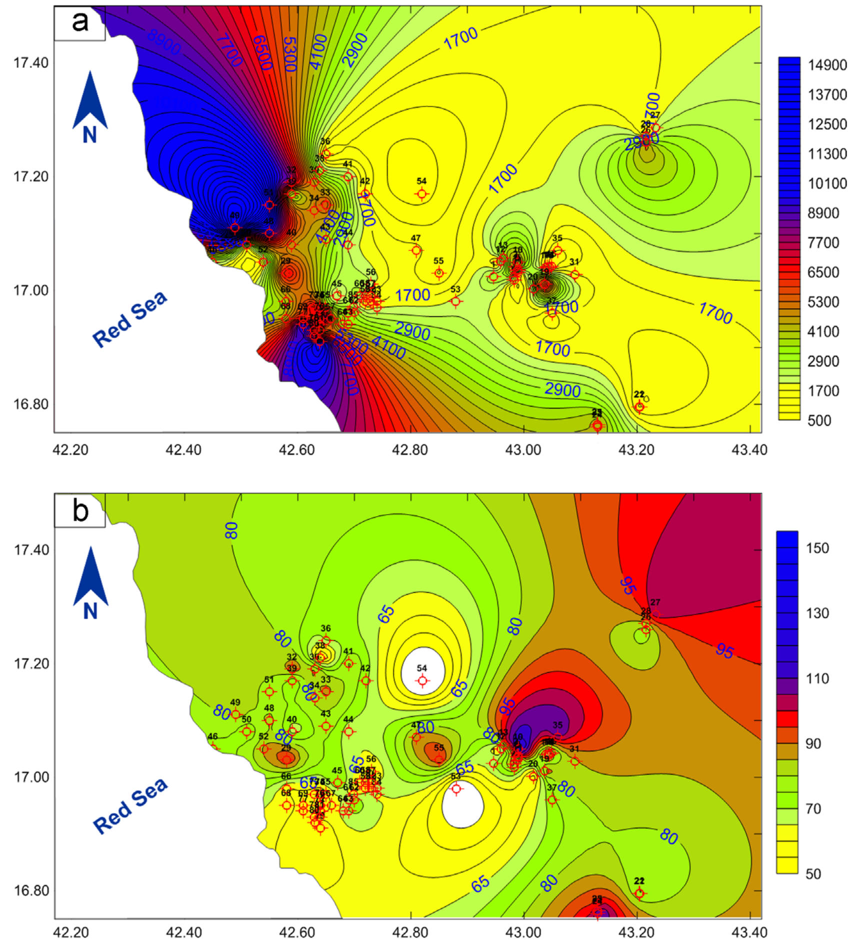

Fig. 12. (a) Electric conductivity map of the Jizan area and (b) the subsurface temperature map of the Jizan area (modified after [8]).

In general, the geothermal fluids/systems are indicated by the low-resistivity blue-colored zones in the interpreted resistivity profiles. A good geothermal reservoir volume with a thickness of 23 m (depths 9.20–32 m) is found at the middle of the resistivity profile KH 1. It represents a good geothermal reservoir that extends more than 80 m in the NE direction (between electrodes 40 and 56). A high resistivity uplift (216–1866 ohm.m) is indicated at the middle of the section (between electrodes 32 and 35). It represents a massive body of the host granitic rocks.

Fig. 17, on the other hand, exhibits a NW–SE trending resistivity profile (line KH 4). It shows one of the major subsurface structural elements that control the movement and ascending of geothermal water in Al Khouba area. A good fault system (NE–SW direction) is indicated between electrodes 32 and 41, bounded by medium to high resistive beds in both sides.

5.4. Geothermal power potential and economic feasibility

Geothermal power plants generate electricity by using thermal energy from sources such as geysers, hot springs, or deep and extremely hot aquifers to drive turbines. Deep geothermal energy can be broken down into two separate categories, power plants and direct-use systems [30]. To know if one and/or both these two categories are appropriate for Al Khouba geothermal resource, a technical feasibility discussion should be made, in conjunction with a preliminary cost–benefit analysis, taking into consideration the accommodation of Saudi electric-grid for the possible geothermal energy production.

5.4.1. Geothermal reserve

Al Khouba geothermal system attains the highest surface temperature (78 °C) in the study area. The estimated reservoir parameters of this hot spring are found to be 144 mW/M^2, 318 kJ/kg and 133 °C for heat flow, discharge enthalpy and subsurface temperature, respectively. According to the surface and subsurface petro-thermal parameters of Al Khouba geothermal system, it is considered as one of the potential resources for possible power generation in Jizan area.

A geothermal reserve study is carried out for estimating the possible potential of Al Khouba hot spring, based on the following assumptions:

- A reservoir area of 2.25 km^2 (1.5 × 1.5 km), reservoir thickness of 500 m and reservoir volume of 1.125 km^3 as concluded from the interpretation of resistivity data.
- Pore volume range of 3–5 p.u. for the fractured granitic rocks.
- Density range of 2.7–2.90 g/cc.
- Temperature difference of 35 °C (initial reservoir temperature of 80 °C – reference temperature of 45 °C).

Assuming the above mentioned parameters, the total stored heat energy of Al Khouba geothermal system is found to be 8.971×10^{15} J for thermal fluids and 1.041×10^{17} J for reservoir rock, with an average value of 1.123×10^{17} J. A geothermal power energy of 17.847 MWt is estimated for Al Khouba hot spring, providing a power plant life of 20 years, recovery factor of 0.2, turbine conversion efficiency of 0.56, and load factor of 0.95. The estimated 17.847 MWt megawatts are considered good for installing a small scale power plant for energy production.

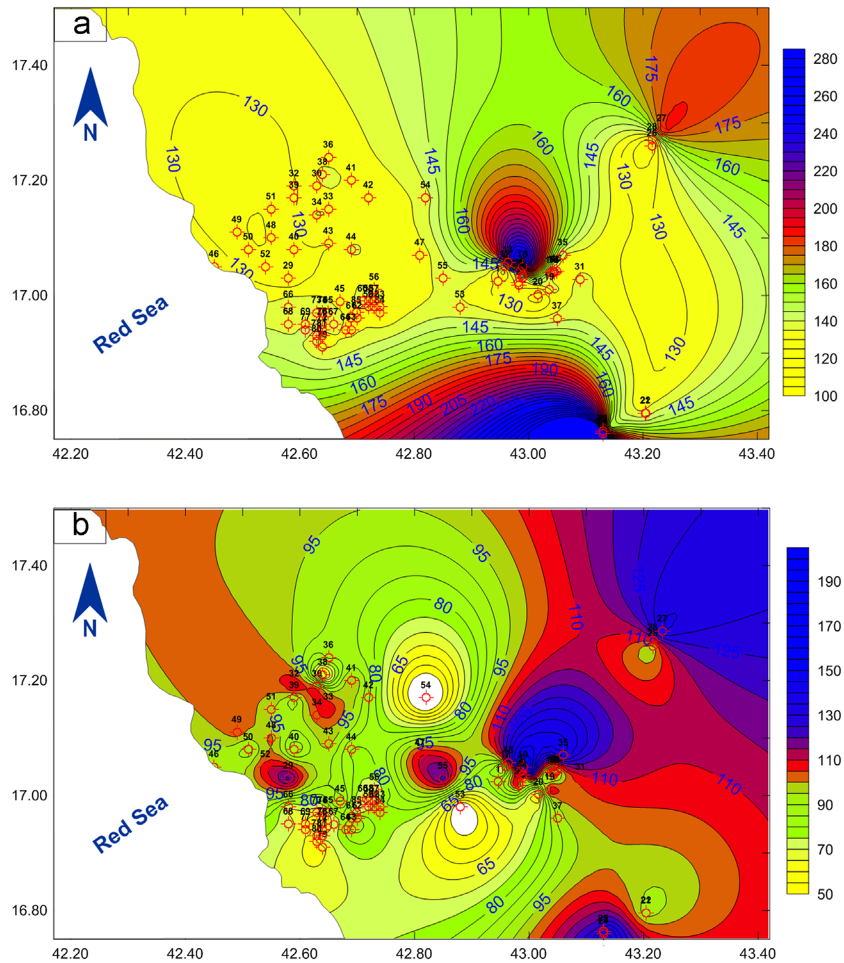

Fig. 13. (a) The discharge enthalpy map of the Jizan area and (b) the heat flow map of the Jizan area (modified after [8]).

5.4.2. A technical feasibility analysis and plausible design for power and heat utilization

A technical feasibility analysis for the possible assessment and development of the geothermal resources Al Khouba area is made. This analysis is preliminary in nature because it is based solely on surface exploration data, as no wells have been drilled on Al Khouba to date. A more specific project feasibility study that considers power plant and field design and operation will be conducted when the results of the exploratory drilling and testing program are completed [26].

The appropriate technology for Al Khouba geothermal resource can be determined once the resource is better constrained. In general, there are three major technologies commonly used to generate electricity from geothermal resources. The three types of plants are the following:

- *Dry steam*: uses geothermal steam directly from a geothermal reservoir that has a fracture system that is entirely steam (220–245 °C).
- *Flash*: geothermal steam is separated from hot water at the surface. The steam is delivered to a steam turbine, while water phase is re-injected into the geothermal reservoir (200–330 °C).
- *Binary cycle*: uses a secondary 'working' fluid (binary fluid) with a lower boiling temperature than water, such as ammonia (Kalina cycle). Heat from the geothermal fluid causes the binary fluid to flash to vapor via a heat exchanger, and the binary vapor is sent through the turbine to generate power.

Regarding Al Khouba geothermal area, the main hot spring is located topographically in a low-to medium accessible area that has good fracture system and good thermal gradients that allow heat to flow and be extracted more easily to the surface. Since the minimum temperature for binary plants is ~120 °C, Kalina cycle seems to be the most appropriate design for energy production from Al Khouba geothermal resource (Fig. 18). Other low-temperature direct applications can be also considered (swimming and refreshments pools, Spa, medical therapy, green houses, etc.).

5.4.3. A cost–benefit analysis

A commercial project financing feasibility study is not possible until exploratory wells are drilled and tested in order to establish resource parameters such as temperature, well deliverability, fluid composition, resource capacity, location and accessibility of the geothermal resource.

The geothermal system at Al Khouba has not been drilled, but exploration data indicate a viable resource that could feasibly support planned development for power production and direct use applications. The resource capacity and the probability of exploration and development success are all dependent on the target. The shallow geothermal resource of 78 °C at the surface (outflow zone) is likely to be accessible. A deeper, hotter resource of >130 °C (i.e., "upflow zone") has a greater access risk but will be targeted. As mentioned above, the binary power plants with low-boiling fluids can be used for possible power production.

Table 2
The estimated subsurface temperature, discharge enthalpy and heat flow values for the hot springs encountered at the Jizan area, using the different geo-thermometer indicators.

Area	Hot spring	Geo-thermometer	Quartz	Chalcedony	Na–K	Na–Ca	Na–K–Ca
Al Ardah	Ain Al Waghrah-1	Subsurf. temp.					
		T_1	129.37	101.85	237.72	79.85	146.02
		T_2	129.24	101.01	–	–	–
		Used			129.31 °C		
		Discharge enthalpy			184 kJ/kg		
		Heat flow			171.95 mW/M^2		
	Ain Al Waghrah-2	Subsurf. temp.					
		T_1	151.98	126.99	262.8	85.51	149.14
		T_1	152.2	124.12	–	–	–
		Used			152.1 °C		
		Discharge enthalpy			188 kJ/kg		
		Heat flow			205.92 mW/M^2		
	Ain Al Waghrah-3	Subsurf. temp.					
		T_1	119.63	91.17	219.81	77.51	141.38
		T_1	119.85	91.12	–	–	
		Used			119.74 °C		
		Discharge enthalpy			239 kJ/kg		
		Heat flow			158.24 mW/M^2		
	Ain Al Waghrah-4	Subsurf. temp.					
		T_1	119.91	91.48	229.4	78.38	144.32
		T_1	120.13	91.41	–	–	–
		Used			119.97 °C		
		Discharge enthalpy			239 kJ/kg		
		Heat flow			158.69 mW/M^2		
	Ain Al Waghrah-5	Subsurf. temp.					
		T_1	122.62	94.44	171.94	89.93	109.68
		T_1	122.82	94.15	–	–	–
		Used			122.72 °C		
		Discharge enthalpy			188 kJ/kg		
		Heat flow			162.86 mW/M^2		
	Ain Al Waghrah-6	Subsurf. temp.					
		T_1	124.57	96.57	168.05	70.75	125.31
		T_1	124.76	96.13	–	–	–
		Used			124.67 °C		
		Discharge enthalpy			255 kJ/kg		
		Heat flow			165.69 mW/M^2		
	Ain Al Waghrah-7	Subsurf. temp.					
		T_1	95.32	64.93	92.77	82.16	79.13
		T_1	95.79	66.65	–	–	–
		Used			95.56 °C		
		Discharge enthalpy			239 kJ/kg		
		Heat flow			121.73 mW/M^2		
Al Khouba	Ain Khulab	Subsurf. temp.					
		T_1	110.84	81.62	133.34	79.72	101.43
		T_1	111.15	82.24	–	–	
		Used			133 °C		
		Discharge enthalpy			318 kJ/kg		
		Heat flow			144.23 mW/M^2		
Bani Malik	Bani Malik-2	Subsurf. temp.					
		T_1	104.64	74.92	144.11	78.03	107.98
		T_1	105.01	76	–	–	–
		Used			104.83 °C		
		Discharge enthalpy			188 kJ/kg		
		Heat flow			136.34 mW/M^2		

However, Table 4 shows a scenario including a full cost analysis for the development of Al Khouba geothermal resource. It includes the expected costs for different exploration, development and plant construction phases. Two exploration shallow temperatures wells and two confirmation wells are assumed to prove resource up to 150 m. Plant construction per MW is assumed to be $1,000,000. A reasonable average cost estimate for a new geothermal power development including exploration, drilling, facilities and power plant is about $1553/kWe, assuming a total cost of about $2,950,000. It is very important to mention here that for accessing high temperature geothermal resource, much deeper wells should be drilled which means increasing of the average tariff for each producible kWe than the estimated one.

5.4.4. Saudi electric grid and geothermal power

In the last decade, the Saudi electric grid has subjected to more developments and improvements. A wide range of the old plants were renewed and many new power plants were built according to the international standards with sufficient capacity to provide for the power needs and to accommodate for the possible further excess of capacity to be sold to the grid.

Jizan city is one of the remote areas in Saudi Arabia where there is insufficient supply of electricity. One big solar-based power plant is installed in Farasan island a few years ago. Some other power and desalination plants are also located in adjacent areas to solve for the power supply problem. Shuqaiq power and desalination complex is one of these plants that is located 140 km north of

Table 3
Example of an output file of the analyses carried out by WATCH 2.1 software for Ain Al Waghrah-2 hot spring, Jizan.

Icelandic water chemistry group				Program Watch, Version 2.1			
3 July 2011		Ain Al Waghrah-2 hot spring, Jizan					
Water sample (mg/g)		Steam sample					
pH/°C	7.50/45.0	Gas (vol%)		Reference temperature, °C			45.0
CO_2	0.00	CO_2	0.00				
H_2S	0.00	H_2S	0.00	Sampling pressure, bar-abs.			3.0
NH_3	1.05	NH_3	0.00	Discharge enthalpy, kg/kg			188.0
B	0.67	H_2	0.00	Discharge kg/s			0.00
SIO_2	129.10	O_2	0.00	Steam fraction at collection:			0.00
Na	621.11	CH_4	0.00	Measured temperature, °C			45.0
K	111.00	N_2	0.00				
Mg	57.00						
Ca	601.00	Liters gas per kg					
F	3.08	Condensate/°C: 0.00/0.0		Condensate (mg/kg)			
Cl	2059.00			pH/°C	0.00/0.0		
SO4	415.00	Total steam (mg/kg)		CO_2	0.00		
Al	0.00	CO_2	0.00	H_2S	0.00		
Fe	0.303	H_2S	0.00	NH_3	0.00		
TDS	8815.00	NH_3	0.00	Na	0.00		
Ionic strength = 0.08241							
Ionic balance: cations (mol eq.) = 0.06207014, anions (mol eq.) = 0.06438300							
Deep water components (mg/kg)				Deep steam (mg/kg)		Gas pressures (bar-abs.)	
B	0.67	CO_2	0.00	CO_2	0.00	CO_2	0.000E+00
SIO_2	129.10	H_2S	0.00	H_2S	0.00	H_2S	0.000E+00
Na	621.11	NH_3	1.05	NH_3	0.00	NH_3	0.155E−06
K	111.00	H_2	0.00	H_2	0.00	H_2	0.000E+00
Mg	57.00	O_2	0.00	O_2	0.00	O_2	0.000E+00
Ca	601.00	CH_4	0.00	CH_4	0.00	CH_4	0.000E+00
F	3.08	N_2	0.00	N_2	0.00	N_2	0.000E+00
Cl	2059.00					H_2O	0.958E−01
SO_4	415.00					Total	0.958E−01
Al	0.00						
Fe	0.303						
TDS	8815.00	Aquifer steam fraction = 0.00					
Ionic strength= 0.08241		1000/T (Kelvin) = 3.14					
Ionic balance: cations (mol eq.) = 0.06207014, anions (mol eq.) = 0.06438301							
Oxidation potential (V): Eh H_2S = 99.99, Eh CH_4= 99.99, Eh H_2 = 99.99, Eh NH_3 = 99.99							
Chemical geo-thermometers (°C)							
Quartz	151.4	Fournier and Potter [24]					
Chalcedony	126.1	Fournier [23]					
Na/K	263.3	Arnorsson et al. [20].					

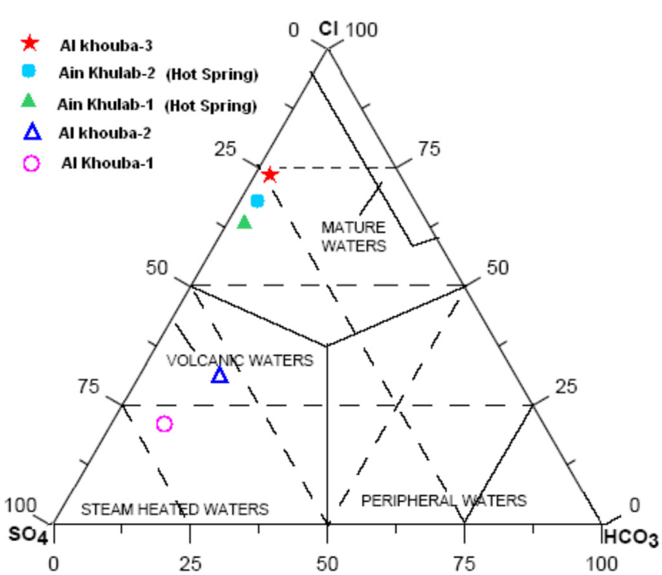

Fig. 14. Water type classification of the hot springs using CL–SO_4–HCO_3 diagram, Al Khouba area.

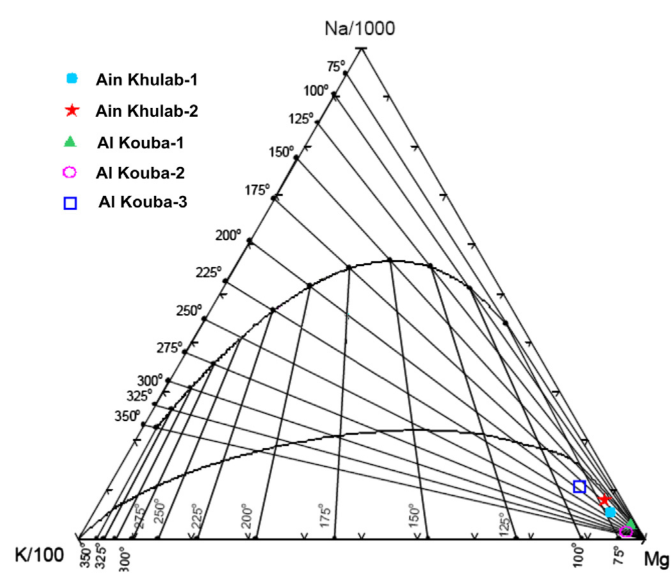

Fig. 15. Giggenbach diagram for the thermal fluids of Al Khouba area.

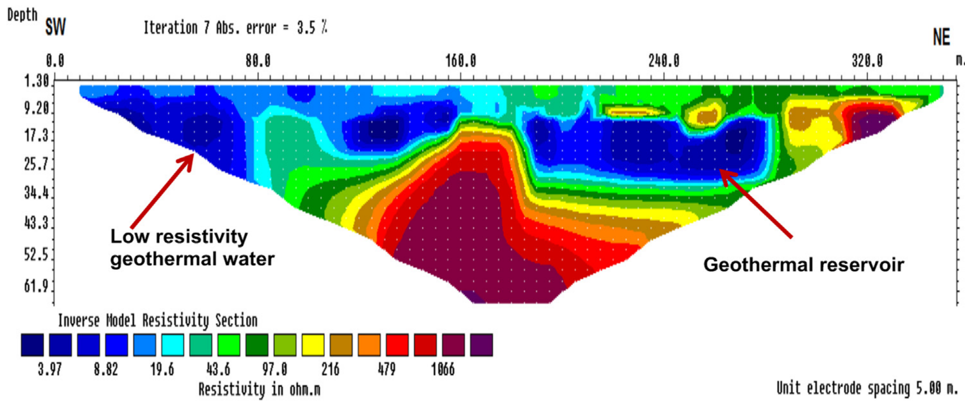

Fig. 16. 2D interpreted resistivity profile (line KH 1) extending SW–NE, Al Khouba area.

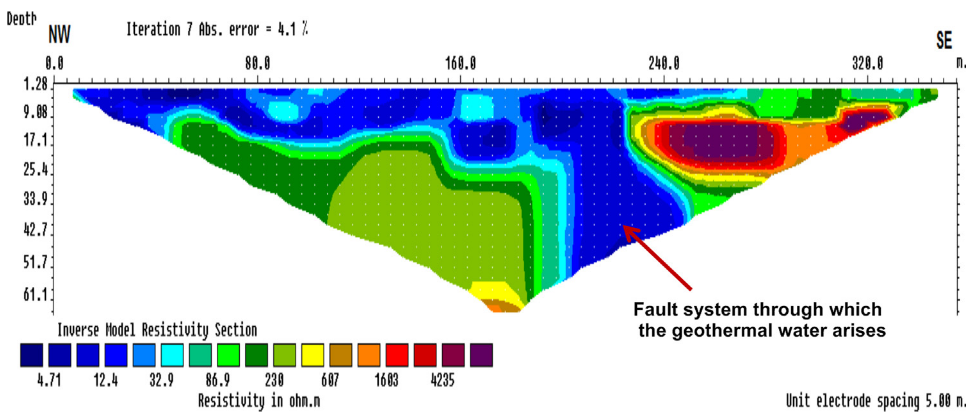

Fig. 17. 2D interpreted resistivity profile (line KH 4) extending NW–SE, Al Khouba area.

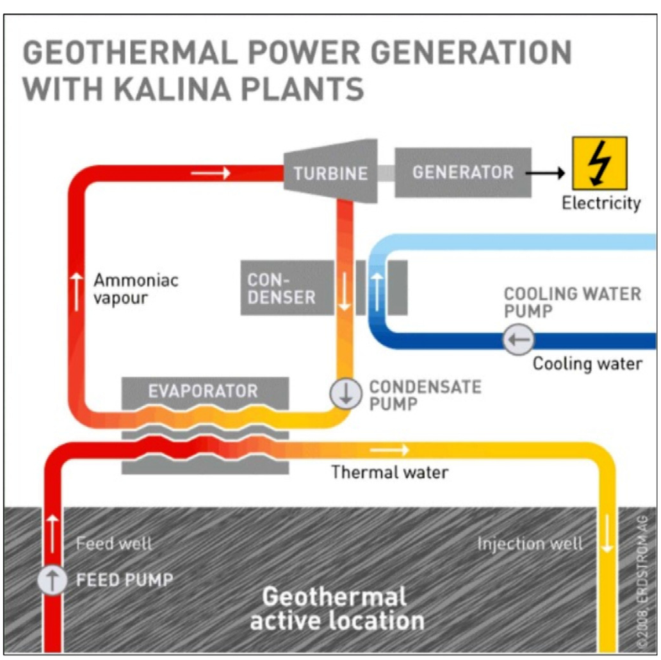

Fig. 18. Design of a simple Kalina power plant.

Jizan and 105 km south of Abha, on the southwestern (Red Sea) coast of the Kingdom of Saudi Arabia. Another big project is the Integrated Gasification Combined Cycle Project (IGCC) that will convert residue gas into electricity for the refinery, as well as exporting around 2.4 GW of power to the nearby Jizan economic city based on refining of 400,000 barrels of oil per day [31].

The geothermal power plants are not yet installed in Saudi Arabia. The Saudi electric ministry has designed more advanced optimization and control technology system that could improve overall plant reliability and deliver operational and maintenance efficiency over the generating life of the facility. It is planned to add 30 gigawatts of generating capacity to the electricity grid and to accommodate all types of energy generations by the end of 2020, including the renewable ones (i.e. geothermal, solar, wind, etc.) [32].

6. Conclusions

The work came as a part from a geothermal project supported by King Saud University. It aims to re-evaluate and investigate the geothermal potentiality of the available geothermal resources located at the southwestern parts of Saudi Arabia (Jizan hot springs) with special emphasis to the main hot spring (Al Khouba). The following are the main points that are concluded from this study:

1. Three promised geothermal locations are found in Jizan area. The first is located at Al Ardah area, where seven hot springs are encountered (Ain Al Waghrah −1 to −7) with a surface temperature range of 43–61 °C. The second geothermal target "Al Khouba hot spring" is located at SW of Jizan, with hot surface temperature of 78 °C. The third geothermal anomaly

Table 4
Cost analysis for geothermal resource exploration and constructions (per kW).

Geothermal exploration and construction costs (per kW)			$2,950,000 total	$1553 per kW
Phase	**Activity details**	**Inputs**	**Calculated values**	*Example values***
Exploration	Initial reconnaissance	**$25,000**		*$250,000–$500,000*
	Surface exploration (geophysics)	**$100,000**		*$1,000,000–$1,500,000*
	Shallow temperature wells (per well)	**$200,000**	Exploration phase subtotal: **$525,000**	*$100,000–$400,000*
	# Temperature wells	**2**		*3–5*
Confirmation	Mobilization of drilling rig to site	**$200,000**		*$250,000–$500,000*
	Cost per meter (full depth wells)	**$500**	Full depth well cost: **$75,000**	*$1500–$2500*
	Well depth, m	**150**		
	# Confirmation wells to prove resource	**2**	Confirmation phase subtotal: **$1,900,000**	*3–4*
	Well testing (total)	**$1,000,000**		*$500,000–$1,000,000*
Total spend to create "bankable" report			**$975,000**	
Development drilling	Number of usable wells from above	**1**	Total production wells: **2**	*1–2*
	Yield of usable well (MW: electricity)	**1**		*7 MW*
	New production wells (yield as above)	**1**	Total development phase wells: **1**	
	Injection wells	**0**		
	Failed wells	**0**	Development phase subtotal: **$75,000**	
			Plant capacity and cost:	
Plant construction	(95% of production well capacity [production wells × well yield])		**1.90 MW**	
	Power plant cost per MW	**$1,000,000**	**$1,900,000**	*$2,000,000–$3,000,000*
Total "overnight"/installed cost			**$2,950,000**	
		Cost per kW	**$1553**	
Operations	O&M (annual $ per MWh) [$20–30]	**25.00**	Annual MWh: **14,980**	*$20–$30*
	Capacity factor	**90%**	Annual O&M: ***$374,490***	
			Annual O&M (% of installed): **12.7%**	

** Example costs taken from GeothermEx (2010) Indonesia data.

"Bani Malik" is located NE of Jizan and is originated from low-temperature (45 °C) highly fractured basement system.

2. Analysis of *Landsat and satellite image* data clarified that Al Ardah and Al Khouba hot springs are located at a medium to low land with little slopes, while Bani Malik hot springs are occupied in a very tough, high (> 650 m above sea level) and steep slope topographic area (complex ridge of Precambrian rocks).
3. Based on the *geo-thermometer* data, good petro-thermal characters (subsurface temperature, discharge enthalpy and heat flow) are assigned for these hot springs. The recognized petro-thermal ranges are found to be 95–152 °C for subsurface temperature, 180–255 kJ/kg for discharge enthalpy and 120–206 mW/M^2 for heat flow.
4. The constructed *ternary diagram* assigns mature water type with the dominance of chlorine and sulfate anions on the expanse of the bicarbonate group. Meanwhile a volcanic water type is assigned for the closely neighboring water wells.
5. The results obtained from *Giggenbach diagram* is matched with those concluded from the detailed geo-thermometer analyses (Na–K thermal lines of 200–220 °C for Al Khouba hot spring).
6. The 2D *geophysical electric resistivity* survey revealed the presence of many geothermal feed zones. The majority of these zones are oriented along directions following the main structural elements in the Red Sea area (NW–SE, ENE–WSW).
7. The reservoir temperature of Al Khouba geothermal system (133 °C) suggests a binary power plant of plausible energy. The estimated *geothermal reserves* are found to be 8.971×10^{15} J for thermal fluids and 1.041×10^{17} J for reservoir rock, with an average value of 1.123×10^{17} J. A *geothermal power energy* of 17.847 MWt is expected providing a plant duration life of 20 years.
8. In terms of power production, the geothermal potential of Al Khouba system can be used in a small-scale industrial level. Other direct low-temperature applications can be also initiated. Recently, some are already progressing by the officials of Al Khouba city.

Acknowledgments

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